Progress in Development of New LLRF Control Systemfor SuperKEKB

T. Kobayashi, K. Akai, K. Ebihara, J. Odagiri, A. Kabe, K. Nakanishi, M. Nishiwaki (KEK, Ibaraki, Japan)
H. Deguchi, K. Harumatsu, K. Hayashi, T. Iwaki, J. Mizuno, J. Nishio, M. Ryoshi (Mitsubishi Electric TOKKI System Corp.,Hyogo, Japan)

Abstract

For the SuperKEKB project, a new LLRF control system has been developed to realize high accuracy and flexibility. High power test of the prototype was performed with the ARES cavity. The feedback control stability with klystron driving agreed well with the low-level evaluation, and very good FB stability of 0.02% in amplitude and 0.02 deg. in phase was obtained in "out of the loop" measurement. Auto tuner control also worked successfully. The start-up sequencer program for the cavity operation and auto-aging program also worked very well.
The temperature characteristics of the system depend largely on band-pass filters (BPF). We tried to tune the BPF to reduce the temperature coefficient. Consequently the temperature dependence was improved to satisfy the required stability.
A new RF reference distribution system was also designed for the SuperKEKB. In this system the reference signal will be distributed by means of "Star" configuration into the RF control sections and transferred optically by using the phase-stabilized optical fiber. Furthermore, phase-lock control function will be implemented to compensate the temperature drift of each transfer line. For this phase stabilization, a new optical delay control system for multi-divided transfer lines was developed originally by applying the direct IQ sampling method, and the its performance was evaluated and the required stability of ±0.1 degrees was obtained.

Upgrade to SuperKEKB

Luminosity : x 40 !
Beam Current: x 2
β_y@IP: x 20 (Emittance: 1/5)

New LLRF Developed

Existing analog systems will be replaced by new digital ones.

- It consists of μTCA-based FPGA boards & PLC (EPICS-Sequencer).
- Linux-OS with EPICS-IOC is installed into each of them. They can be operated remotely via EPICS-Channel Access.
- Hardware is common for both of ARES & SC Cavity. (Also both softwares are much the same.)
- EPICS record names will be consistence with the present systems.
- Klystrons (LLRF) : Cavity unit = 1 : 1 (SuperKEKB)

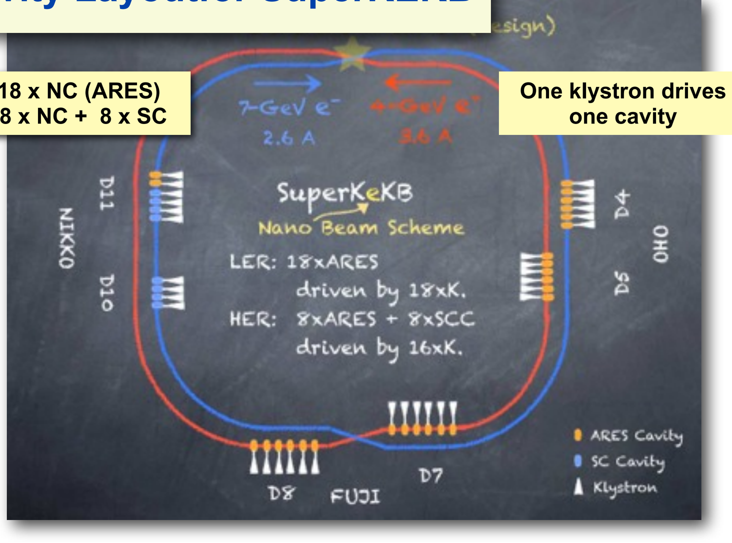
RF Stability Requirements

for acc. gradient	+/- 1%	+/- 1 deg.
Our target value for LLRF System	+/- 0.3% in Amplitude	+/- 0.3 deg. in Phase

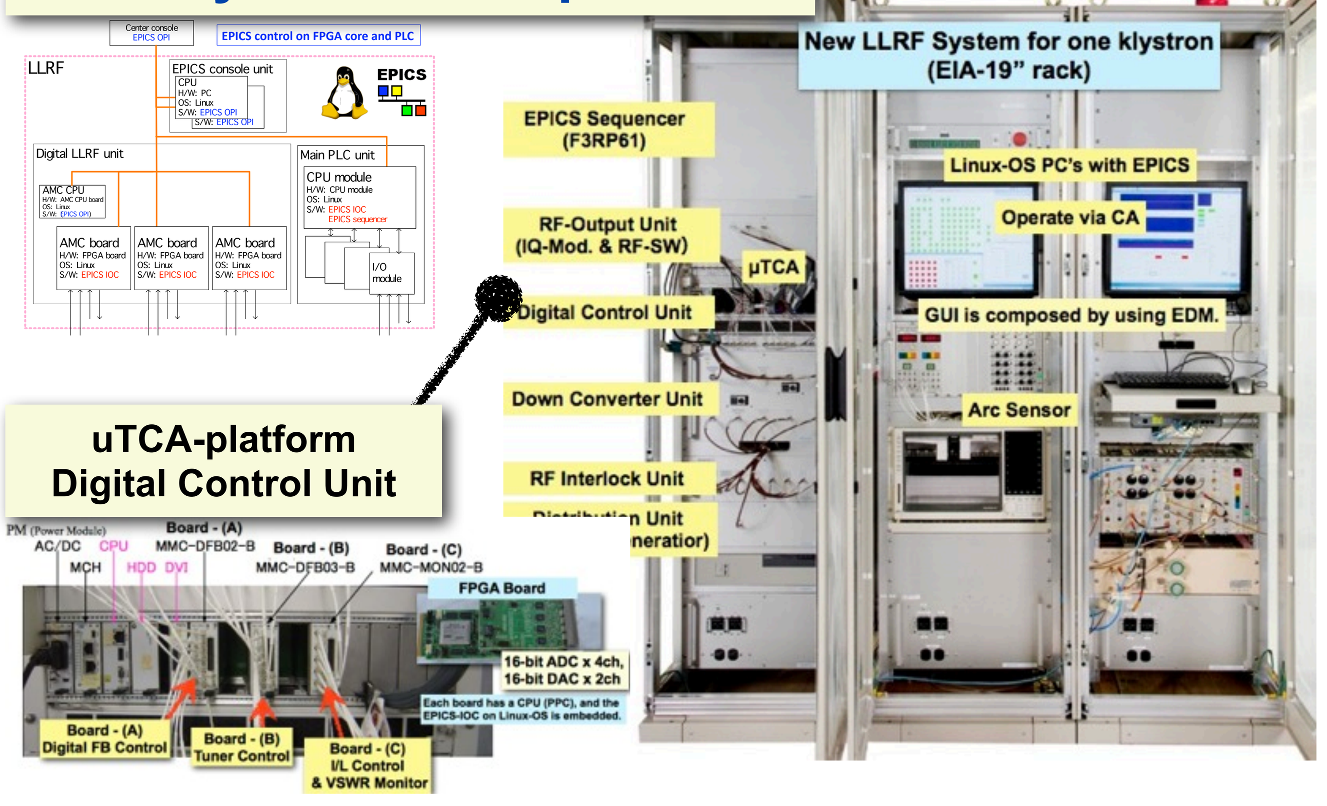
Cavity Layoutfor SuperKEKB

LER: 18 x NC (ARES)
HER: 8 x NC + 8 x SC

One klystron drives one cavity

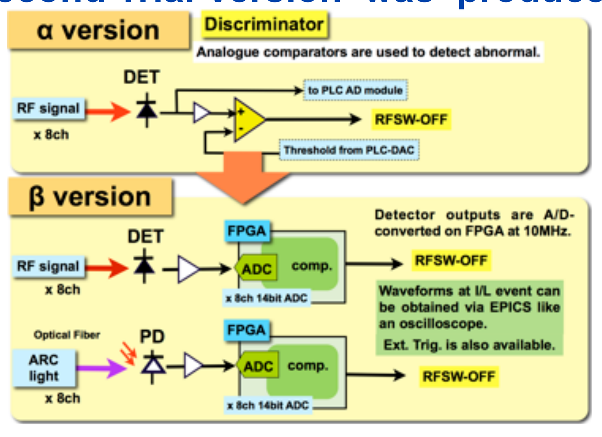


LLRF System for SuperKEKB



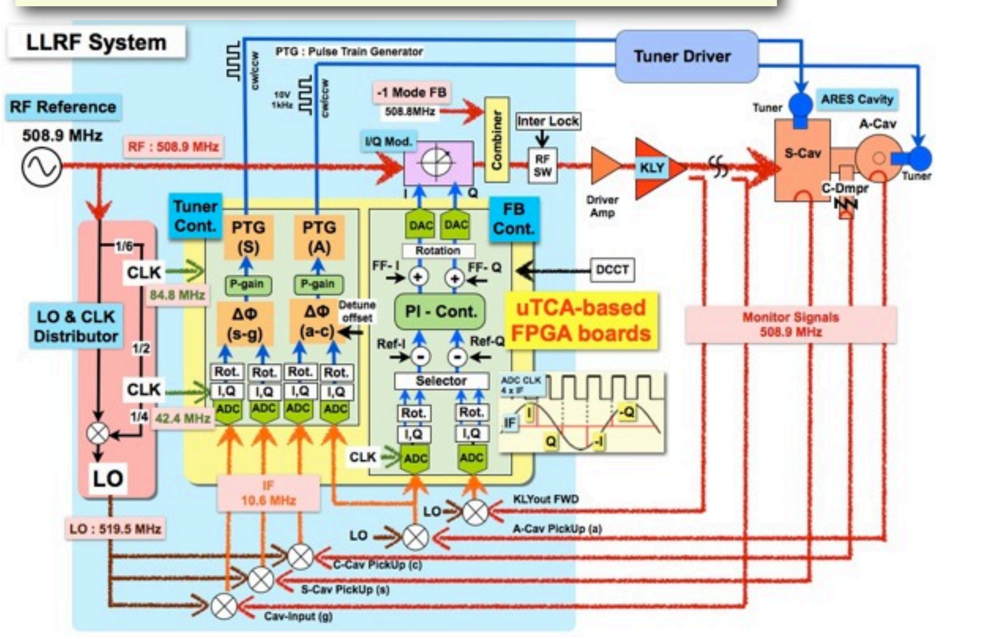
Upgrade of new LLRF to β-version

Second Trial Version was produced.



The second trial model (β-version) has been produced and high power test was performed.
The main difference between α and β-version is the discriminator. In the α-version, For discrimination (RF-I/L), analogue comparators are used to detect the abnormal. The threshold is given from PLC-DAC.
On the other hand, for the β-version, digital sampling method is adopted. Detector outputs are A/D- converted on FPGA at 10MHz. The ADC is 14-bit. In this way, the waveforms at I/L event can be obtained via EPICS like an oscilloscope.
Ext. Trig. is also available.

Block diagram for ARES Cavity



Improvement of Thermal stability

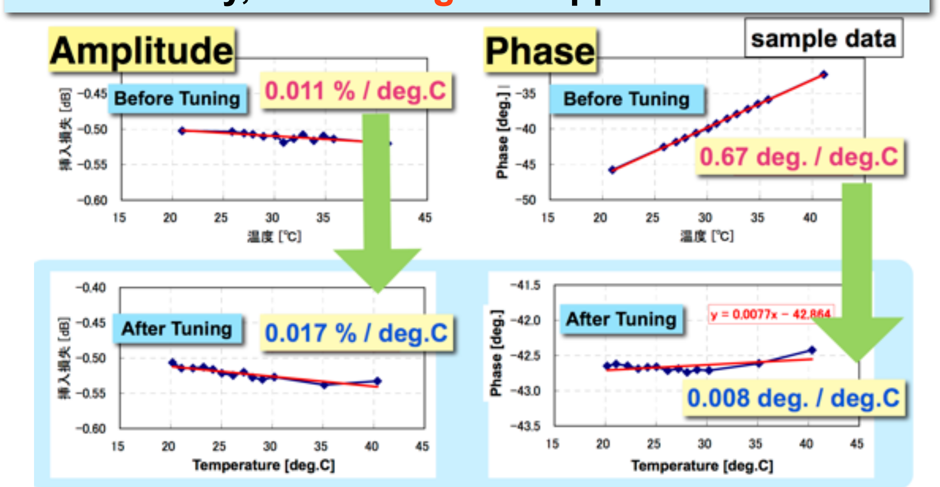
BPF type Change

α-ver. Lumped Constant Circuit Type
β-ver. Cavity Type (K&L - 4FV50)

for good regularity in characteristics between manufacture lots.

BPF Fine Tuning

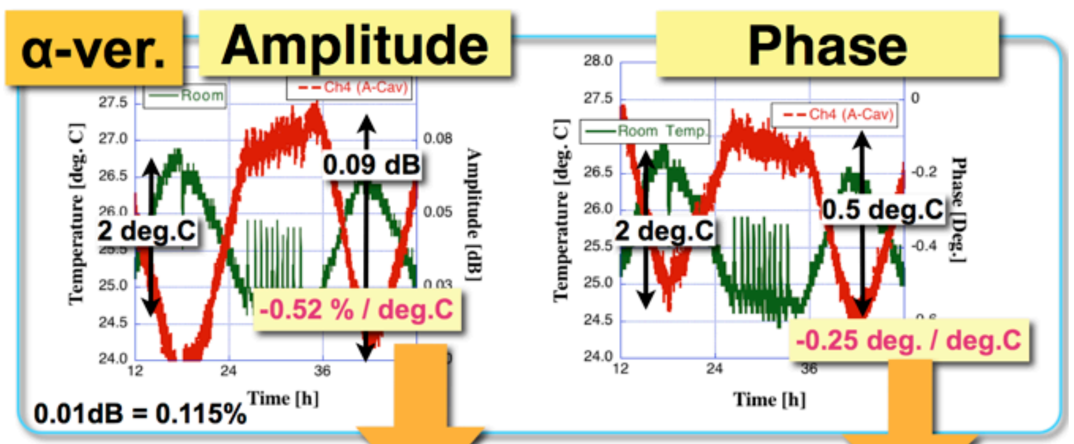
Additionally, fine tuning was applied to all BPF's.

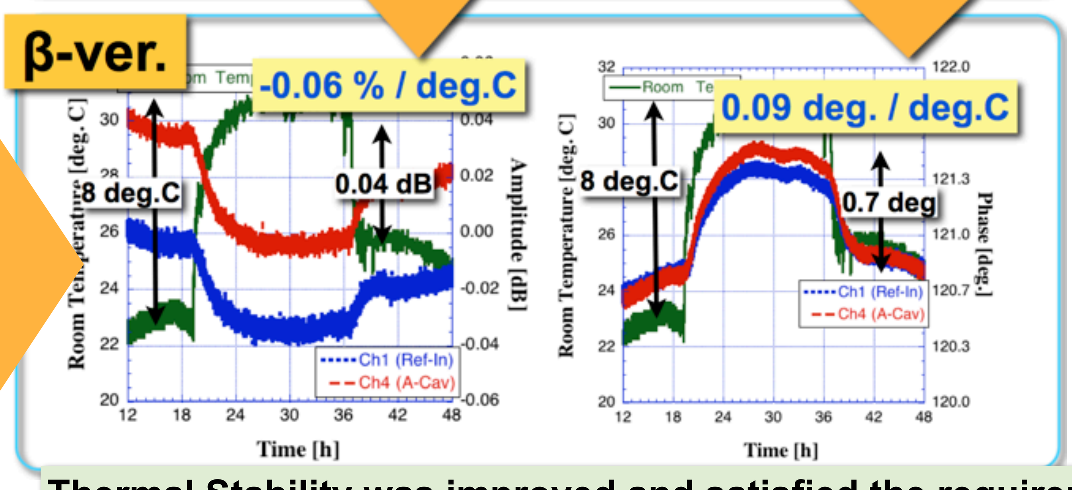


For the improvement of thermal stability, first, we changed the type of BPF for the β-Version. In the α-Version, Lumped Constant Circuit Type was used. On the other hand, in the β-Version, cavity type BPF was chosen. Because cavity type has better regularity of characteristics between manufacture lots.
Furthermore, additionally fine tuning was applied to all BPF's. After tuning, the phase property was improved to be quite small.
The amplitude property is enough small although before the tuning. But the phase tuning also affects the amplitude tuning. So amplitude property was slightly degraded.
The tuning of both is not independent, it is pretty difficult work.

Ambient Temperature Change : about +/- 2 deg.C

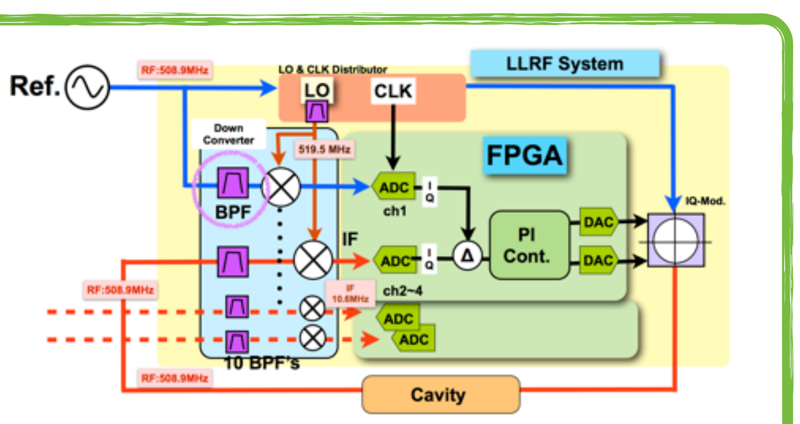
Acceptable Temp. Coefficient	0.1%/deg.C in Amplitude 0.1 deg./deg.C in Phase





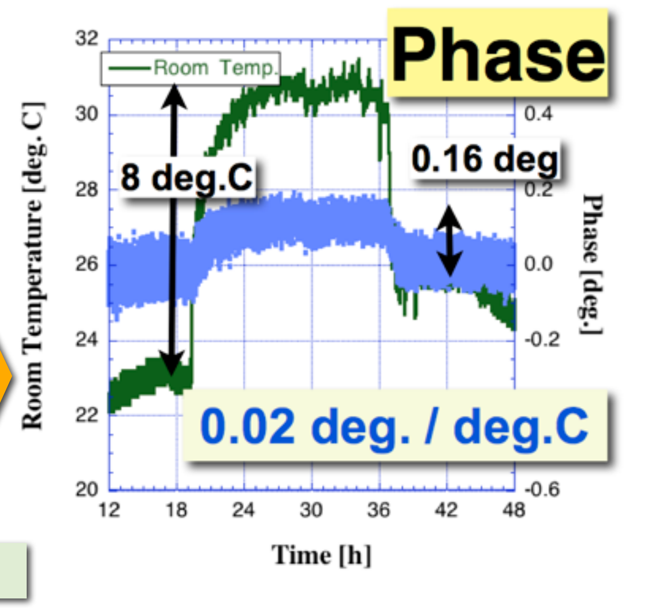
Thermal Stability was improved and satisfied the requirements!

These are measured results of the thermal stability of the system. (Comparison between α-version and β-version.) Trend graph of Amplitude and Phase few days are plotted. Green line indicates the room temperature. Red line corresponds to cavity-pickup channel. Blue line corresponds to the reference channel.
As the results, in the β-version, the stability of these values satisfies the requirements.



From the evaluation of each RF element device, it is found that the main factor is BPF property in the downconverter for the temperature dependency.

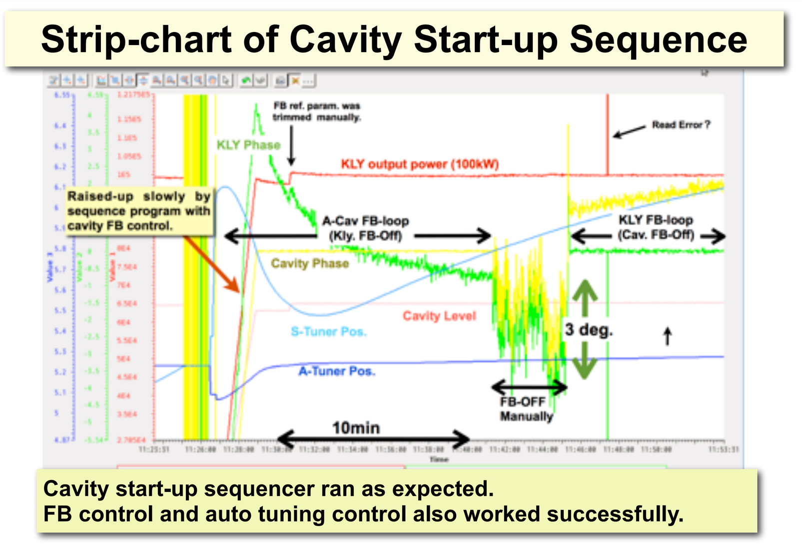
Ch4 can be compensated with the reference channel. (Ch4-Cha1)



Furthermore, if the cavity-pickup channel is calibrated by the reference channel constantly, the phase stability can be improved more. This plot is the compensated case with the reference channel. So the red plot in this plot is canceled by the blue plot. As the result, about 0.02 deg. / deg.C can be expected in phase stability.

High Power Test

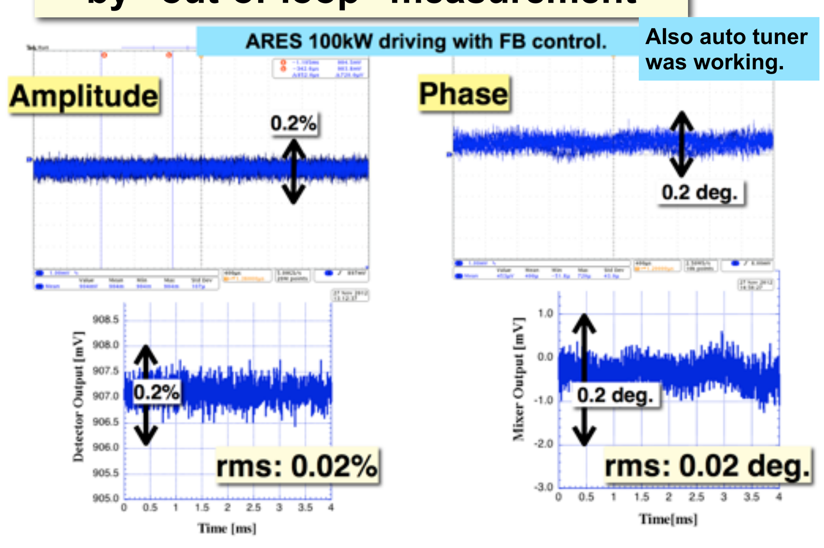
Strip-chart of Cavity Start-up Sequence



Cavity start-up sequencer ran as expected.
FB control and auto tuning control also worked successfully.

This shows the strip-chart at the cavity start-up sequence for about 30-minute duration. Red line indicates the klystron output power, and the faint red is cavity level. The cavity power was raised up slowly by sequencer program with cavity FB control active.
Blue and cyan lines are tuner positions. Accelerating cavity and Storage cavity, respectively. So auto tuning control was working successfully and the tuners were moving (to make resonance).
In this region, the FB loop was opened manually. Without FB control, the klystron phase fluctuates by about 3 degrees due to DC voltage variation. After then, Klystron FB loop was closed.

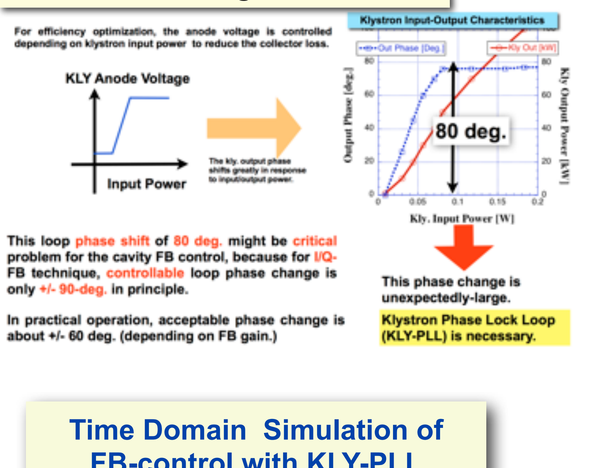
Short Term Stability by "out-of-loop" measurement



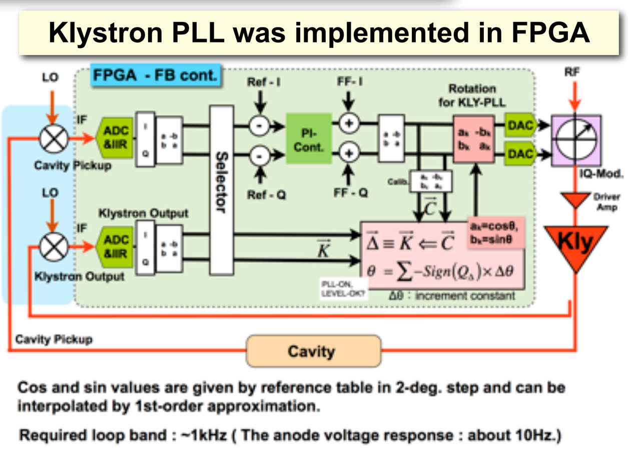
FB control stability was evaluated in the high-power operation. This plot shows the oscilloscope data of 4-ms time duration under cavity FB control with the auto tuner control .
Small beat can be found in the phase, but it is negligible small for our specification.
As shown, very good stability was obtained.
(The stability in r.m.s is) 0.02 % in amplitude and 0.02 degree in phase.

Klystron Phase Lock Loop

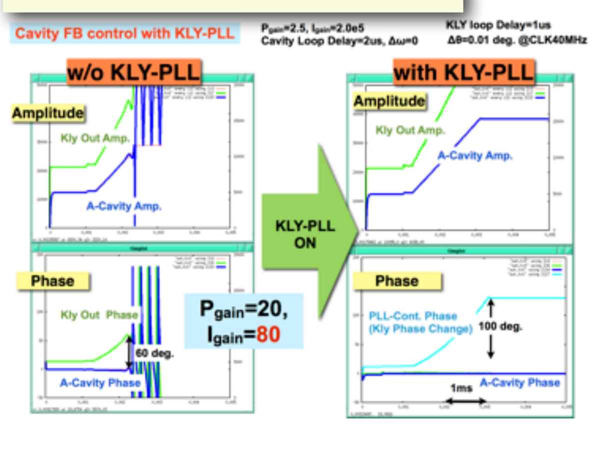
Klystron Phase Change due to Anode Voltage Control



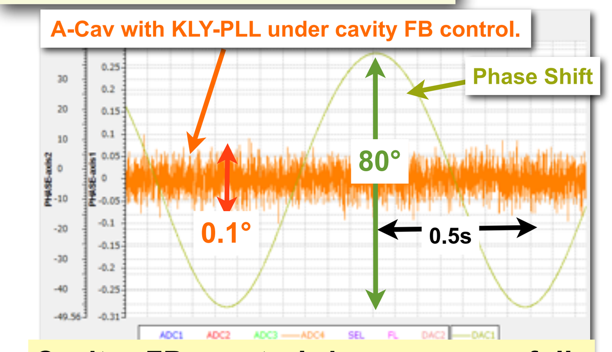
Klystron PLL was implemented in FPGA



Time Domain Simulation of FB-control with KLY-PLL



Performance Evaluation Result

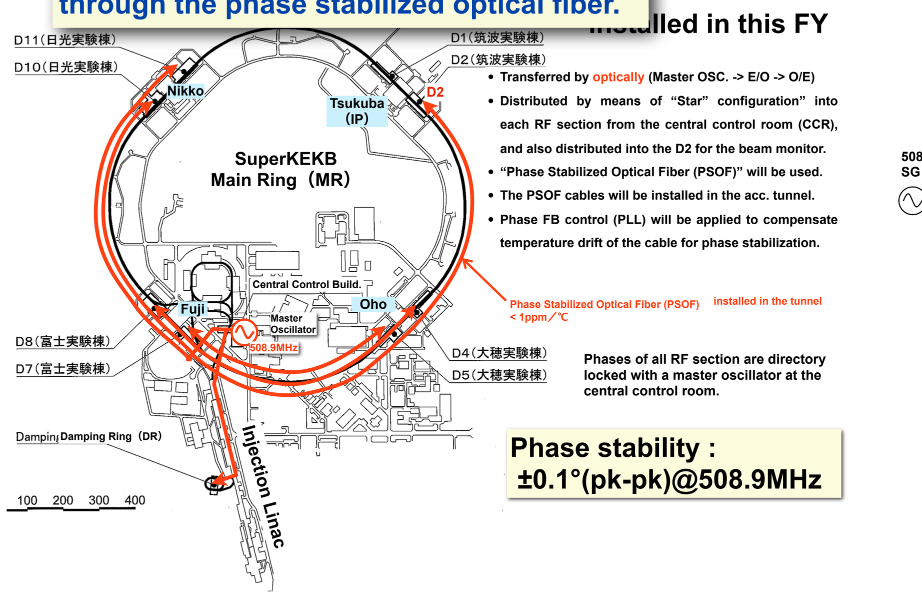


Cavity FB control is successfully working with KLY-PLL while loop phase is changing in 80-degs.

Klystron phase lock loop (KLY-PLL) was implemented in the FPGA digitally with FB-control. This is the illustration of implementation of the kLY-PLL.
For the klystron phase lock, additional phase rotation function is inserted for I/Q modulation. The klystron phase is detected and calibrated by output phase as the reference.
Theta will be accumulated by a increment constant to cancel the klystron phase shift. Then the phase rotation parameters, cosθ, sinθ are given. Cos and sin values are given by reference table in 2-deg. step and interpolated by linear approximation.
The required loop band is supposed to be about 1kHz, because the anode voltage response is about 10Hz.

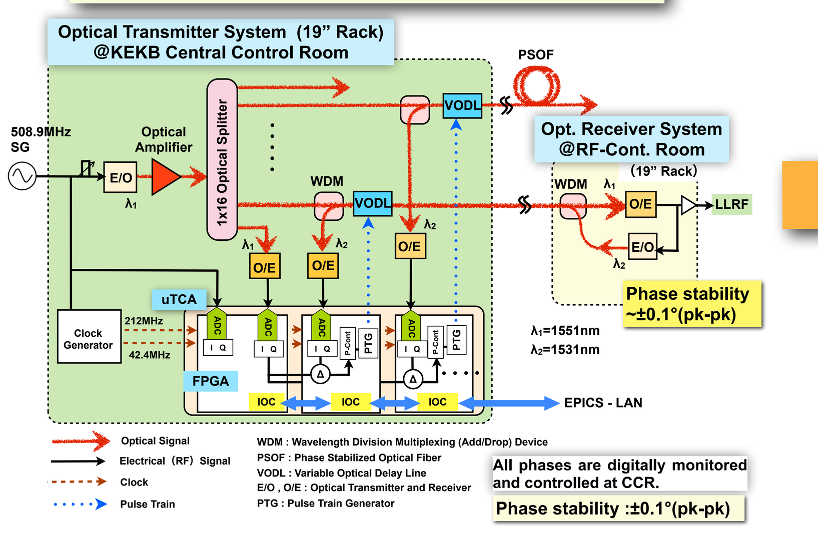
RF Reference Distribution

Distributed by means of star configuration through the phase stabilized optical fiber.



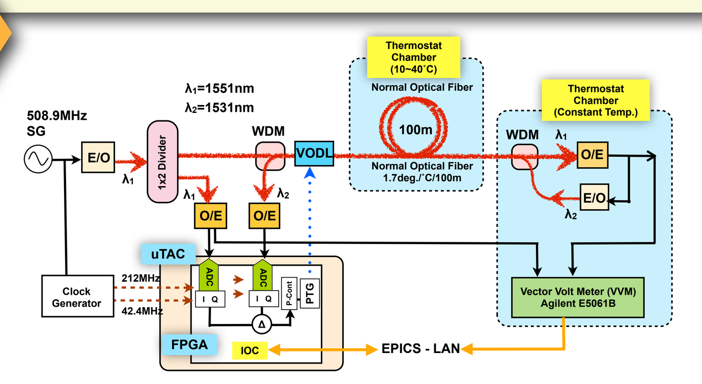
Phase stability : ±0.1°(pk-pk)@508.9MHz

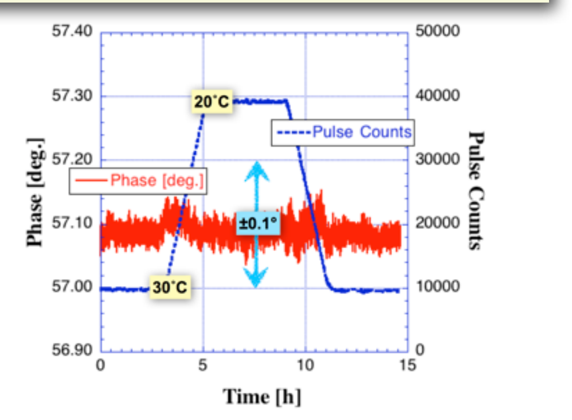
Optical Transmitter and Receiver System with Phase Lock Loop.

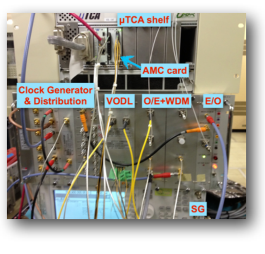


Block diagram of the optical transmitter & receiver system.
The transmitter system is located at central control room, and the receiver systems are at each RF section control Room.
Reference signal is optically divided and transferred into each RF section from central control room (CCR). The transferred signal is returned back in the same fiber cable to the central control room for the phase drift compensation. Then, digitally, the phase of the retuned signal is measured by using uTCA-platform FPGA with direct sampling method, and then a variable optical delay lined (VODL) is controlled to cancel the phase change. The wavelength of the backward signal is different from the forward one. For the isolation, the WDM devices are used.
All phases are digitally monitored and controlled at CCR.

Performance of VODL control for the PLL

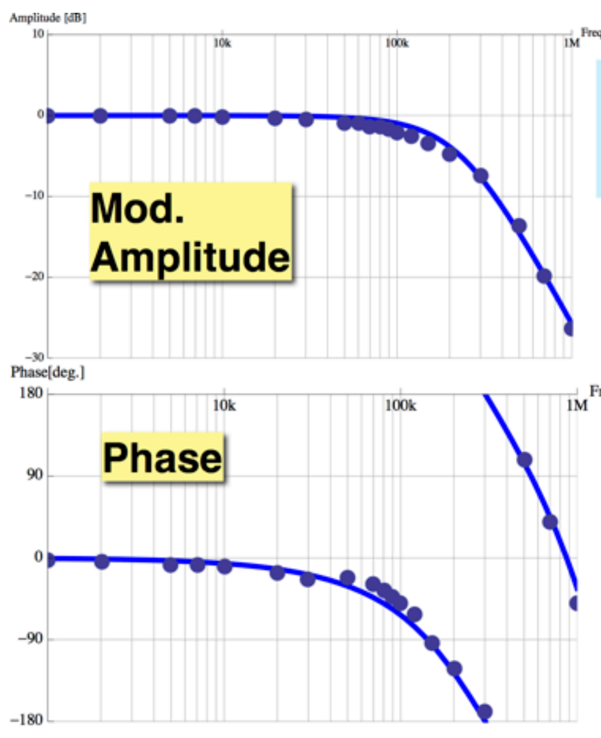






VODL control (PLL) performance was evaluated. Phase stability of transferred signal was measured by using a vector volt meter (VVM) as temperature of transferring optical cable was changed. Normal optical fiber of 100m, which has large thermal coefficient (1.7 deg./deg.c/100m), was used in this transmission.
Measured result is shown in right plot. Red linesindicates the phase of transfer signal measured by VVM (the left axis). Dashed blue line is pulse counts of VOLD control (the right axis), which corresponds to phase change of 17 deg due to temperature change of the cable.
As the result, required phase stability of ±0.1 deg. was successfully obtained by this PLL system with VODL control.

Measured Klystron Frequency Characteristics

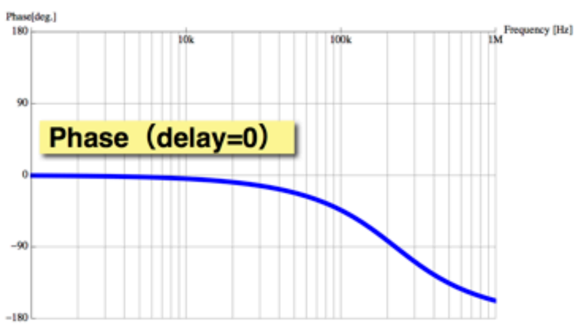


Delay (T_d)

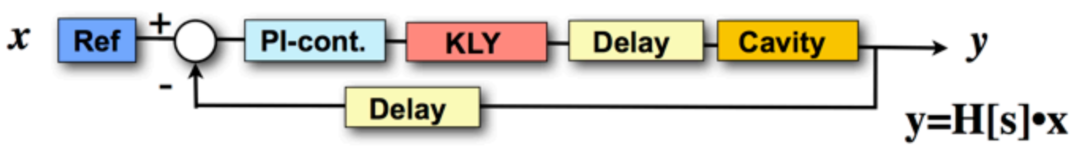
$$H_{kly}[s]=\frac{1}{1+s/\omega_{kly}+s^2/\alpha}\bullet e^{-s\cdot T_d}$$

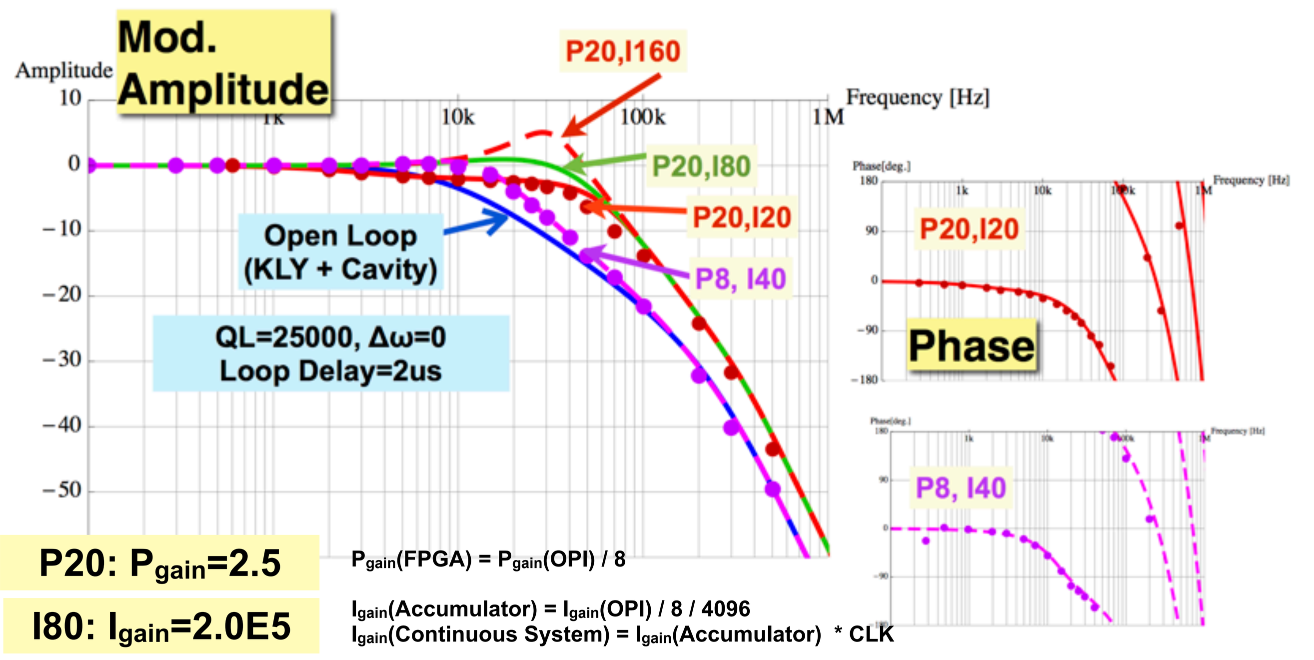
ω_{kly}=130kHz

α=2.1x10^{12} T_d=650ns



Bode Plot of FB-Control (1)





P20: P_{gain}=2.5

I80: I_{gain}=2.0E5

P_{gain}(FPGA) = P_{gain}(OPI) / 8

I_{gain}(Accumulator) = I_{gain}(OPI) / 8 / 4096

I_{gain}(Continuous System) = I_{gain}(Accumulator) * CLK

Bode Plot of FB-Control (2)

Cavity response to disturbance inside closed loop (e.g. DAC noises) .